

The latest STAR results on quarkonium production *

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We report the latest results of J/ψ , $\psi(2S)$ and Υ production in the dielectron decay channel at mid-rapidity, from the STAR experiment. We present J/ψ cross section measurements in $p + p$ collisions at $\sqrt{s} = 200$ and 500 GeV, as well as the first measurement of the $\psi(2S)$ to J/ψ ratio at $\sqrt{s} = 500$ GeV. We also show J/ψ and Υ production in heavy ion collisions: J/ψ nuclear modification factors (R_{AA}) in Au+Au collisions at $\sqrt{s_{NN}} = 200, 62.4$ and 39 GeV and in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV, ΥR_{AA} in d +Au, Au+Au and U+U collisions at $\sqrt{s_{NN}} = 200, 200$ and 193 GeV, respectively. The results are compared to different model calculations.

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1. Introduction

It was proposed that in high energy heavy-ion collisions quarkonium states can be used as probes of Quark-Gluon Plasma (QGP) formation. Due to the Debye-like color screening of the quark-antiquark potential in the hot and dense medium, quarkonia are expected to dissociate and this “melting” can be a signature of the presence of a QGP [1]. Studies of production of quarkonium states in heavy-ion collisions can provide insight into the thermodynamic properties of the hot and dense medium [2]. However, in the medium created in heavy-ion collisions quarkonium yields can be enhanced, relative to $p + p$ collisions, due to statistical recombination of heavy quark-antiquark pairs. Also, effects related to the “normal” nuclear matter, so called cold nuclear matter (CNM) effects: (anti-)shadowing, initial-state parton energy loss, final state nuclear absorption or the Cronin effect, can alter the quarkonium production. Therefore, it is difficult to distinguish the color screening effect from the other effects. J/ψ with $p_T > 5$ GeV/ c , are expected to be almost not affected by the recombination and CNM effects [3] at the RHIC

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energies. Also Υ are considered as cleaner probes of the QGP, compared to J/ψ , because of the negligible statistical recombination and co-mover absorption [4, 5]. Systematic measurements of quarkonium production as a function of centrality and transverse momentum, for different colliding systems and collision energies may help to understand the quarkonium production mechanisms in heavy-ion collisions as well as properties of the created medium.

2. Charmonium measurements

STAR has measured inclusive J/ψ production in $p + p$ collisions at $\sqrt{s} = 200$ and 500 GeV and $\psi(2S)$ production at $\sqrt{s} = 500$ GeV through the dielectron decay channel at $|y| < 1$. The p_T spectrum measurements at $\sqrt{s} = 200$ GeV are shown on the left panel of Fig. 1, where low- [6] and high- p_T [7] results are shown separately as squares and circles, respectively. Data points are compared to different models of J/ψ production. The predictions of the Color Evaporation Model (CEM) [8] and NLO calculations within the nonrelativistic QCD (NRQCD) effective field theory that include both color-singlet and color-octet contributions (NLO CS+CO) [9], describe the data quite well. Both predictions are for the prompt J/ψ production. The Color Singlet Model (CSM) [10] for the direct production underpredicts the measured cross section. On the other hand, RHIC J/ψ polarization measurements [11] show different trend than the prediction of NRQCD [12], and are in agreement with the CSM [13]. The right panel of Fig. 1 shows J/ψ cross section as a function of x_T (defined as $x_T = 2p_T/\sqrt{s}$) at $\sqrt{s} = 500$ GeV, for p_T range of 4-20 GeV/c. The STAR result (full circles) is compared to measurements at different energies. The J/ψ cross section follows the x_T scaling: $\frac{d^2\sigma}{2\pi p_T dp_T dy} = g(x_T)/(\sqrt{s})^n$, with $n = 5.6 \pm 0.2$ at mid-rapidity and $p_T > 5$ GeV/c for a wide range of colliding energies [14]. The left panel of Fig. 2 shows a ratio of $\psi(2S)/J/\psi$ production (full circle) compared to measurements of other experiments at different colliding energies, in $p + p$ and $p+A$ collisions. The STAR result is consistent with the observed trend and, with the current precision, no collision energy dependence of the $\psi(2S)$ to J/ψ ratio is observed.

Effects of the hot and dense medium created in heavy-ion collisions are evaluated using the nuclear modification factors (R_{AA}), defined as the ratio of the particle yield in $A + A$ collisions to that in $p + p$ collisions, scaled by the number of binary collisions. J/ψ R_{AA} measurements have been done in Au+Au and U+U collisions, as a function of transverse momentum, and for different centrality bins (represented as the number of participant nucleons, N_{part} , in a collision). First, we show measurements of R_{AA} in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV vs N_{part} , for low- (< 5 GeV/c) [16] and high- p_T (> 5 GeV/c) [7] inclusive J/ψ production. As can be seen on the left panel of Fig. 3, R_{AA} decreases with increasing centrality, and the high- p_T J/ψ suppression level is lower than the low- p_T one. Since high- p_T J/ψ are expected to be almost not affected by the recombination or CNM effects at

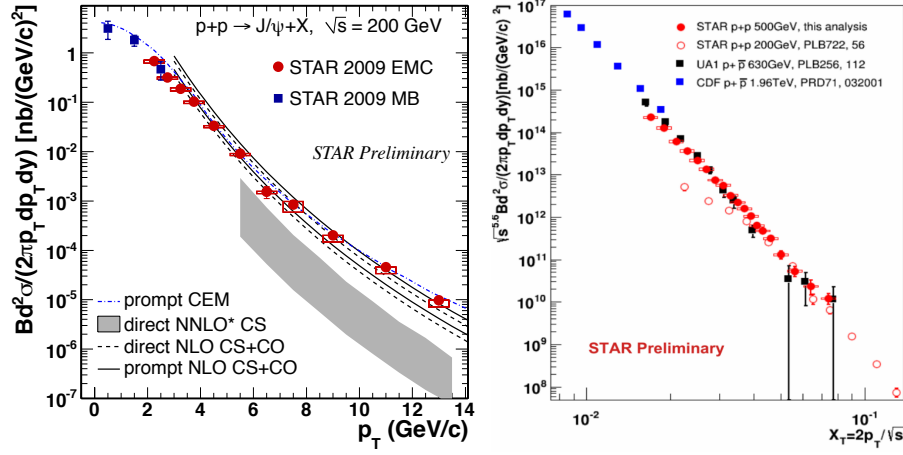


Fig. 1. Left: J/ψ invariant cross section vs p_T in $p+p$ collisions at $\sqrt{s} = 200$ GeV at mid-rapidity at low [6] and high p_T [7] shown as squares and circles, respectively, compared to different model predictions [8, 9, 15]. Right: J/ψ invariant cross section multiplied by $\sqrt{s}^{5.6}$ vs x_T in $p+p$ collisions at $\sqrt{s} = 500$ GeV at mid-rapidity shown as full circles compared to measurements at different energies.

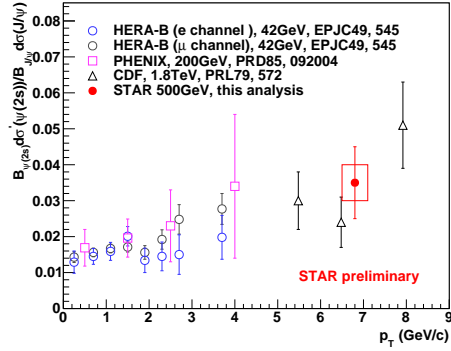


Fig. 2. Ratio of $\psi(2S)$ to J/ψ in $p + p$ collisions at $\sqrt{s} = 500$ GeV from STAR (the full circle) compared to results from other experiments at different energies.

RHIC energies, the suppression in central collisions points to the color screening effect and thus formation of the QGP. The Liu *et al.* [17] model is in agreement with the low- and high- p_T R_{AA} results, while the prediction of Zhao and Rapp [3] is consistent with low- p_T data but underpredicts the high- p_T R_{AA} . Both models take into account direct J/ψ production with the color screening effect and production via the recombination of c and \bar{c} quarks.

The interplay between recombination, CNM effects and direct J/ψ production can be studied by changing energies of colliding ions. The right panel of Fig. 3 shows low- p_T J/ψ R_{AA} in Au+Au collisions for different colliding energies,

$\sqrt{s_{NN}} = 200, 62.4$ and 39 GeV. The observed suppression is similar for all these energies, and results are well described by the model of Zhao and Rapp [3]. The significant uncertainties come from lack of precise $p + p$ measurements at 62.4 and 39 GeV, instead Color Evaporation Model calculations [18] are used as baselines. STAR has also performed an analysis of J/ψ R_{AA} in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV, where the initial energy density can be up to 20% higher than in Au+Au collisions, in the same centrality bin [19]. The centrality-integrated U+U result is shown in the right panel of Fig.3, as a full circle. The suppression level is consistent with what is measured in Au+Au collisions.

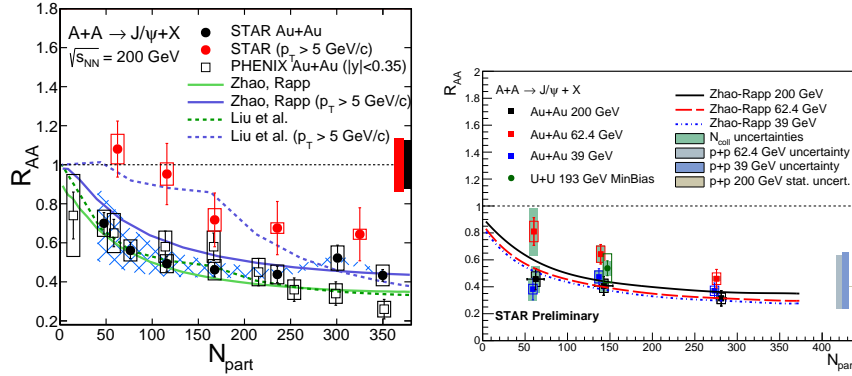


Fig. 3. Left: Low- (< 5 GeV/c) and high- p_T (> 5 GeV/c) J/ψ R_{AA} as a function of N_{part} in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity ([7, 16]) with two model predictions ([3, 17]). Right: J/ψ R_{AA} as a function of N_{part} in Au+Au collisions at $\sqrt{s_{NN}} = 200, 62.4$ and 39 GeV at mid-rapidity with model predictions. As a full circle the minimum bias U+U measurement at $\sqrt{s_{NN}} = 193$ GeV is also presented.

3. Υ measurements in d +Au and A+A collisions

Υ measurements in STAR have been performed in $p + p$, d +Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5] and in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. The left panel of Fig. 4 shows the nuclear modification factor for d +Au collisions, R_{dAu} , as a function of rapidity. The result is compared to CEM calculations with shadowing based on the EPS09 nPDF parametrization [8] presented as the shaded area, model of Arleo *et al.* where suppression of Υ is due to initial-state parton energy loss [20] presented as the dashed line, and the model combining both shadowing and energy loss, presented as the dashed-dotted line. The strong Υ suppression at $y \sim 0$ cannot be explained by the current predictions of CNM effects in d +Au collisions.

The right panel of Fig. 4 presents the nuclear modification factors as a function of N_{part} , for $\Upsilon(1S + 2S + 3S)$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

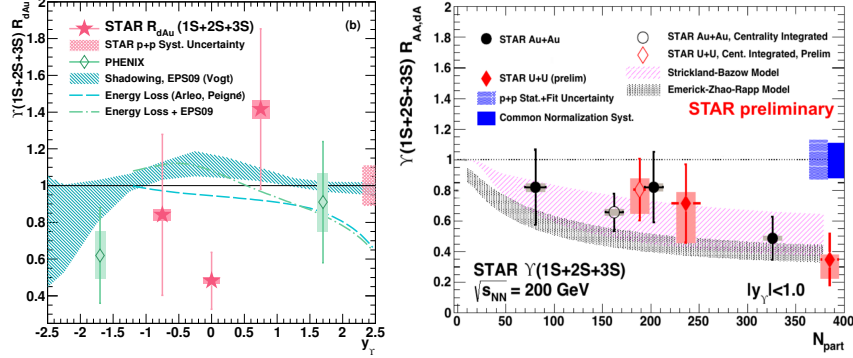


Fig. 4. Left: R_{dAu} as a function of rapidity for STAR [5] (stars), and PHENIX [21] (diamonds) results, compared to different model predictions [20]. Right: R_{AA} as a function of N_{part} for $\Upsilon(1S + 2S + 3S)$ at $|y| < 1$, Au+Au [5] (circles), and U+U (diamonds) collisions, compared to two model predictions (shaded areas) [22, 23].

(full circles) and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV (full diamonds), at $|y| < 1$. A strong suppression is observed both in Au+Au: $R_{AuAu} = 0.49 \pm 0.13$ (Au+Au stat.) ± 0.07 ($p + p$ stat.) ± 0.02 (Au+Au syst.) ± 0.06 ($p + p$ syst.) and U+U collisions: $R_{UU} = 0.35 \pm 0.17$ (stat.) $^{+0.03}_{-0.13}$ (syst.), in the most central collision. The R_{AA} results in both colliding systems show similar trend. The nuclear modification factor for $\Upsilon(1S)$ ground state shows also a suppression in the most central 10% Au+Au collisions [5] that is in agreement with the prediction of the Liu *et al.* model [24] where the suppression is mostly due to the dissociation of the excited states. The data are consistent with model predictions of Strickland and Bozov [22], and Emerick *et al.* [23], that include hot-nuclear-matter effects. Calculations of Emerick *et al.* in addition take into account the CNM effects. STAR has also observed the full suppression of $\Upsilon(2S + 3S)$ states, the 95%-confidence upper limit for R_{AA} in the centrality range of 0-60% is $R_{AA}(2S + 3S) < 0.32$. However, understanding of CNM effects is important for a better interpretation of results from heavy-ion collisions.

4. Summary

In this proceedings we present STAR latest results of the J/ψ , $\psi(2S)$ and Υ production in $p + p$, $d+Au$, Au+Au and U+U collisions at different colliding energies. J/ψ and Υ suppression in central heavy-ion collisions and the indication of the complete suppression of $\Upsilon(2S + 3S)$ suggest formation of the Quark-Gluon Plasma. However, no strong dependence on the colliding energy or colliding system of the suppression is observed.

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